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THEORETICAL CHARACTERIZATION OF SQUARE PIEZOELECTRIC MICRO ULTRASONIC TRANSDUCER FOR UNDERWATER APPLICATIONS

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ABSTRACT

There are numerous advantages of employing MEMS based transducer within underwater applications. This work utilized MEMS based acoustic transducer for underwater applications. Two common types of micro ultrasonic transducer are capacitive (cMUT) and piezoelectric (pMUT). In this study, square pMUT will be characterized using finite element method (FEM). The model consist of ZnO film as a piezo active layer and nickel aluminum bronze ($CuAl_{10}Ni_5Fe_4$) as the electrodes, adhered on the silicon on insulator (SOI) wafer. Structural parameters namely diaphragm width and thickness were manipulated for resonance frequency tuning. Then, the model undergone piezoelectric and modal analyses to obtain the relationship between applied voltage and generated pressure and vise versa. Next, device sensitivity was estimated. After characterization, model design has been finalized to carry fundamental frequency of 50 kHz. It was also estimated that device transmitting voltage response is 139 dB re 1 µPa/V on the surface of the transducer while its receiving response was estimated at - 69 dB re 1 V/µPa. Developed model should be fabricated in order to validate the findings and this will be included in our future works.

1. INTRODUCTION

Micro fabricated acoustic transducer has become extremely popular for numerous terrestrial and underwater applications. Owing to the advancement in microelectronics fabrication technology, variety of MEMS based sensor still keeping their fast growing pace with many advantages tailing; small in size, cheap production, built in electronics, low noise level, synergized with bio-inspired system and higher sensitivity to name a few [1-2]. Among them, two common sensing mechanisms were either capacitive (cMUT) or piezoelectric (pMUT). Basic structure of the pMUT [3] is shown in Fig. 1. It must at least consist a layer of piezo active film sandwiched between two electrodes on a support structure usually silicon based substrate. The device should be able to deform due to applied electric field.

This electrostriction process is reversible, so when the device changes in dimension, similar electric field will be generated. Several types of piezoelectric materials are quartz (permanently polarized), PZT ($Pb(Zr,Ti)O_3$), zinc oxide (ZnO) and aluminum nitride (AlN). PZT ceramic has become a choice for its strong piezoelectricity however, recent findings on this particular area have focus on ZnO for lower fabrication cost followed with simpler characterization techniques [4-5] and on this basis, this study is focusing on utilizing ZnO film.

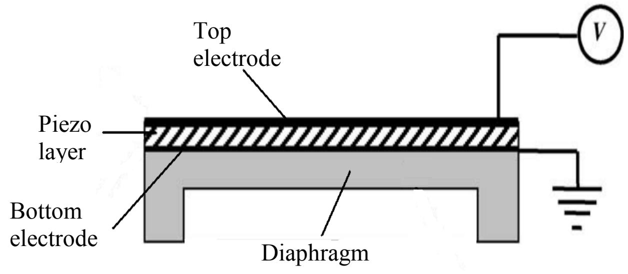

Figure 1. *Basic structure of pMUT*

Due to strong conductivity, gold, platinum and copper were frequently utilized as electrodes in micromachined acoustic transducers. However, at 5.21×10^{12} pS/µm of conductivity, nickel aluminum bronze alloy can also being utilized as conductor layer in MUTs. Perhaps, by having the same materials with the housing, the layer is expected to have better acoustic impedance match between piezo layer and housing material. However, an effort to improve acoustic impedance matching can also be done by manipulating structural parameters as demonstrated elsewhere [6]. First part of this study involves the selection of the right diaphragm width for our targeted frequency range. Next, selected model was undergone piezoelectric and modal analyses. Finally, it was proved that by utilizing alternative materials such as ZnO and nickel aluminum bronze, the performance of the developed model was comparable to other MUTs.

2. MODEL PARAMETERS

Suggested model consist of seven layers of different materials as illustrated in Fig. 2. The top part of the model is the electroded ZnO while bottom part is basically the silicon on insulator layer (SOI) wafer. Top and bottom part of the model was expected to adhere each other by the layer of adhesive, most probably a polymer based material. Only partial top surface of the ZnO is electroded. For simplicity, unelectroded region on top of the ZnO surface was assumed to carry zero electric field. The structure of the diaphragm only consist of first six layer of top and bottom electrodes, ZnO piezo active layer, Cytop adhesive material, silicon and silica of SOI wafer. Bottom silicon layer was assumed to be etched using ion etch with silica as a stopping layer. Preliminary thickness of each layer were 0.2 µm for both electrodes, 40 µm for ZnO piezo active layer, 5 µm for adhesive layer (Cytop), 10 µm for upper silicon layer and 2 µm for silica layer. Total thickness, H initially was 57.4 µm.

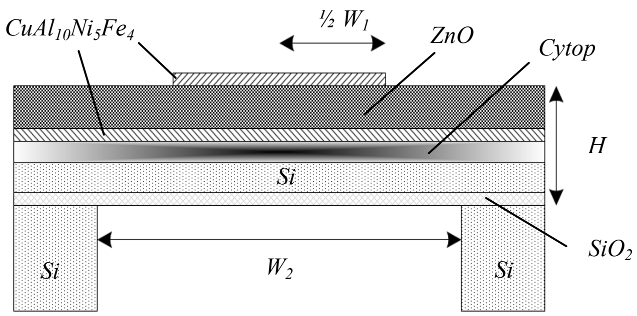

Figure 2. *Model structure*

For finite element meshing, the model was simplified with only the vibrating part left as shown in Fig. 3. There were five important surfaces on the model. First is the outer edge of the model, S_{fix}. Next surface is on the top of the whole model, S_{top} whom will receive inbound acoustic signal. Another two surfaces located on top and bottom of ZnO layer and being in contact with top and bottom electrodes, denoted with S_{pzt} and S_{pzb} respectively in Fig. 3 and lastly the lowest surface which the bottom part of the diaphragm, S_{bottom}.

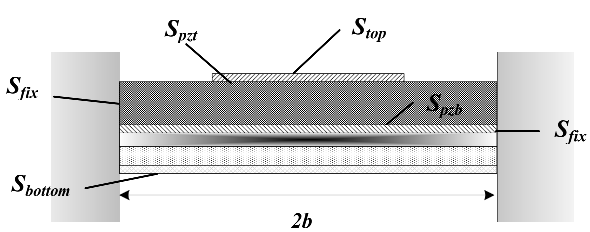

Figure 3. *Simplified model for FEA*

The assumption of the model to be a multilayered plate with all outer surface clamped at the fix edge has been demonstrated using circular shaped model. Another crucial structural parameter was the ratio of top to bottom electrode widths. However, the influence of those on device performance will not be discussed in this report and the values of 0.85 were taken for the whole analyses [7].

3. METHODOLOGY

Important properties for each material are listed in Table 1. Piezoelectric coefficients of all material were set to be zero except for ZnO. As not stated in the table, the density of ZnO film was set at 5.68×10^{-15} kg/µm^3. Young's modulus, E and Poisson's ratio, υ were taken as the measure of elastic coefficients of all isotropic materials. As the electrodes, aluminum bronze was set to carry 5.21×10^{12} pS/µm of electrical conductivity.

Table 1. *Material properties*

Material	ρ (10^{-15} kg/µm^3)	E (10^4 MPa)	υ
SiO_2	2.70	7.30	0.17
Si	2.50	16.90	0.30
Cytop	2.03	0.12	0.38
$CuAl_{10}Ni_5Fe_4$	7.58	11.50	0.33

Simplified model in Fig. 3 was then being split into two separate regions with different mesh setting. Both regions however have undergone the same Manhattan bricks meshing. First region, consist of electroded ZnO layer and second region, complies remaining Cytop, Si and SiO_2 layers. First region was meshed with smaller element size than second region. Similar method for a square pMUT using PZT as a piezo active layer has been validated elsewhere [8]. An equivalent circuit was employed to represent performance parameters [9] as shown in Fig. 4. The circuit consists of capacitor, C_m inductor, L_m and resistor, R_m that are in series correspond to a resonance. Individually, C_m, L_m and R_m represent elasticity or modal compliance, vibrating mass and modal loss respectively. Stack capacitance, C_o is a capacitance formed by two electrodes on the surface of ZnO.

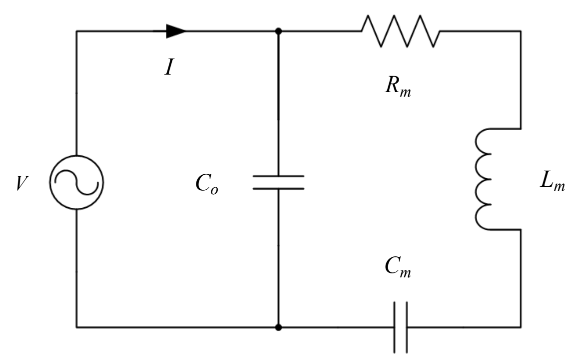

Figure 4. *Equivalent electrical circuit for the model*

4. ANALYSIS

Analysis section has been divided into three parts. In the first part, the width and thickness of the model have been manipulated for fundamental frequency tuning. Next, acoustic transmitting capability was identified. Then finally, receiving response of the transducer was determined.

4.1. Frequency Tuning

In this analysis, the width of the model was varied from minimum of 1000 µm up to 5200 µm maximum while keeping the top to bottom electrode width ratio constant at 0.8. Preliminary thickness of all materials also has been kept unchanged. Modal analysis was applied on the model by shorten the two electrodes. The frequency values obtained from the first vibrational mode of the model. Fig. 5 shows the result from this analysis. It was observed that for the square shaped pMUT, fundamental frequency will dropped significantly with the increment of the diaphragm width. Fitted line plot in Fig. 5 shows very strong cubical relationship with coefficient of determination at 98.5 % between diaphragm width and fundamental frequency. By varying the width from 1 to 5 mm, frequency difference was found to be greater than 350 kHz.

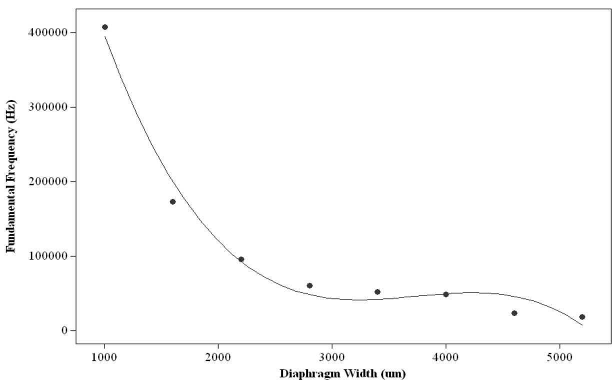

Figure 5. *Fundamental frequency at various diaphragm widths*

Nonlinear relationship from the above analysis makes it only suitable for rough estimation of model's fundamental frequency. For better design flexibility and fine tuning, another structural parameter that can be manipulated was thickness of the vibrating diaphragm. In the next analysis, the width of the diaphragm was held constant at 2800 µm and the piezo active layer was thinned down. It was observed that by reducing the thickness of the diaphragm, the fundamental frequency of the device will also decrease. Relationship between piezo active layer thicknesses with corresponding fundamental frequency is shown in Fig. 6.

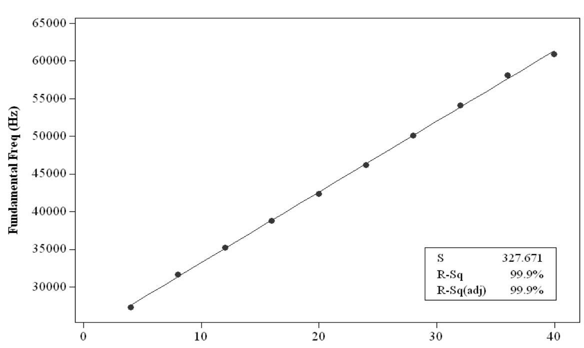

Figure 6. *Fundamental frequency versus ZnO layer thickness*

4.2. Transmitting Voltage Response

This part of analysis estimates the transmitting voltage response of the device for underwater sound projecting applications. By neglecting the housing and impedance matching layer between transducer and the load (water), sound pressure level (SPL) was estimated at the surface of the device. Scalar potential was supplied at the S_{pzt} surface with bottom electrode (S_{pzb}) as a reference. With the present of electric field and the ZnO was polarized at the thickness direction, maximum displacement at the center of the diaphragm was observed. Then, static pressure was applied upward at S_{bottom} surface (Fig. 3) to mimic the effect of the piezoelectricity. Finally, transmitting voltage response was estimated by using simple interpolation. Fig. 7 shows the result of piezoelectric analysis and Fig. 8 pictures relationship between applied pressures with the maximum displacement at the center of the diaphragm from modal analisys. From previous analysis, ZnO thickness was set at 28 µm and the diaphragm width was 2800 µm producing 50 kHz of fundamental frequency. By fixing those parameters and undergone the interpolation, it was found that equivalent pressure produced that correspond to 1 V of drive voltage was 9.3 Pa or 139 dB with reference to 1 µPa of SPL. In other word, the transmitting voltage response was estimated at 139 dB re 1 µPa/V at the surface of the transducer.

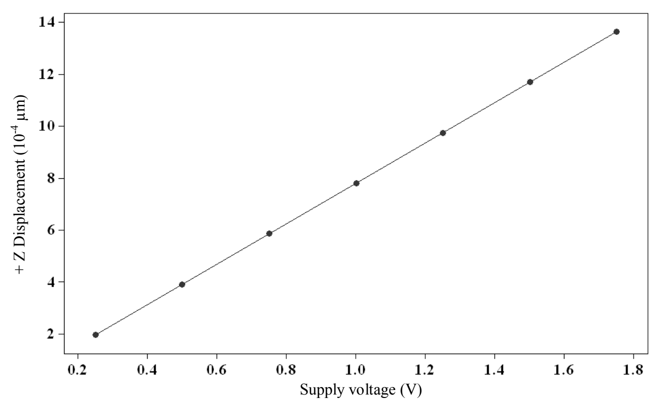

Figure 7. *Maximum displacement of diaphragm correspond to drive voltage*

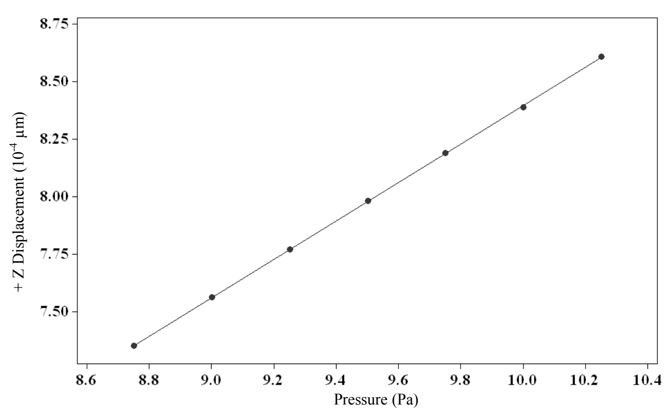

Figure 8. *Equivalent displacement when outbound static pressure was applied*

4.3. Receiving Response

Receiving response can be defined as output voltage generated by the transducer per 1 µPa of sound pressure at the surface of the transducer. In this analysis, sound pressure was replaced with the static pressure at S_{top} surface. The pressure was directed downward so that displacement of the diaphragm occurs in the negative direction of the Z axis. For each applied pressure, minimum displacement at the center of the diaphragm was observed and the result is shown in Fig. 9. Then, piezoelectric analysis was conducted but this time a potential was applied at the S_{pzb} surface with reference to S_{pzt} surface so that the diaphragm also deflect on the same direction when the pressure is applied previously. Relationship between applied voltage and diaphragm deflection is illustrated in Fig. 10. Analysis revealed that 1 µPa of pressure only capable to deflect the diaphragm at 8.13×10^{-11} µm. From the interpolation, this amount of deflection is caused by the supply voltage of 130 nV, or – 69.39 dB re 1 V. Thus, receiving response at the surface of the transducer was estimated at – 69.39 dB re 1V/µPa. In other word, when 69.39 dB re 1µPa of SPL reach the transducer, it will generate 1 V of output voltage.

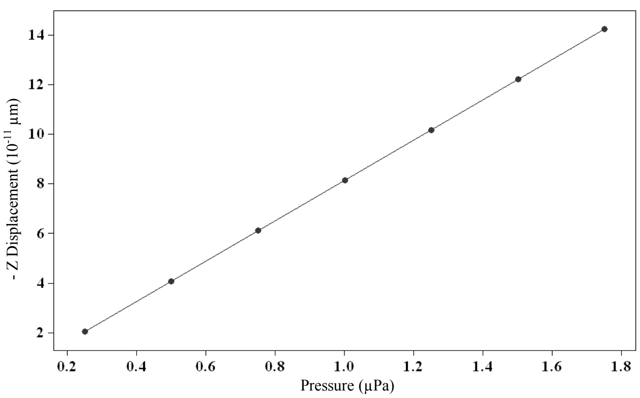

Figure 9. *Equivalent displacement when inbound static pressure was applied*

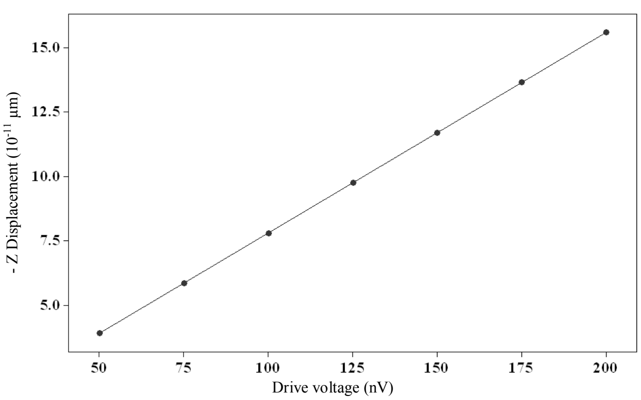

Figure 10. *Minimum displacement of diaphragm correspond to drive voltage*

5. RESULT AND DISCUSSION

After all analyses, final transducer specification can be simplified in Table 2. There was a previous finding [9] which relate the value of L_m in an equivalent circuit in Fig. 3 with the modal mass of the vibrating device. It can be suggested here that for rough estimation of fundamental frequency, the study on the width of the diaphragm is crucial. However, in order to tune the frequency finely, the parameter that should be considered is thickness of the diaphragm. Most importantly, by reducing the thickness of the piezo active layer, the value of stack capacitance will also changing since the distance between two electrodes plate are changed. The effect of reduced stack capacitance is out of the scope of this paper. For estimation of the transmitting voltage response, it is very important that the measurement of SPL is usually done 1 m away from the transducer. Actual performance of the transducer might be lower from the projected value. It is also important to note that both transmitting voltage response and receiving response were usually given as a function of frequency. In this work, limited simulation time has driven the result being estimated by neglecting the frequency function of the input stimuli. Having those value of transmit and receive response indicate that the device is suitable for transceiver operation.

Table 2. Final specification of pMUT

Parameter	Value
Diaphragm width	2800 µm (2.8 mm)
Diaphragm thickness	45.40 µm
Resonance Frequency	50 kHz
Transmit Response	139 dB re 1 µPa/V
Receive Response	- 69 dB re 1V/µPa

6. CONCLUSIONS

Square shape pMUT has been successfully characterized. The device consists on ZnO film as a piezo active layer and nickel aluminum bronze alloy as the electrodes. Frequency tuning of the device has been employed by varying the width of the diaphragm and changing the thickness of the piezo active film. Final frequency of 50 kHz was selected and the device has undergone response analyses. Device transmitting voltage response and receiving response have been successfully estimated by utilizing simple interpolation method.

7. ACKNOWLEDGEMENT

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